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Small staggered cuts were made in unidirectional prepreg to allow it to stretch. The cuts were made either just locally where required for a complex mold, or throughout the whole prepreg. Three tests were performed: uni-axial tensile tests of flat specimens, mold conformability tests to evaluate manufacturability, and manufacturing and structural tests of round tubes. The cuts reduced the tensile strength by less than 20%. The conformability tests used a complex shaped mold for part of a radome and the locally cut prepreg significantly simplified layup and reduced

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Stretchable Unidirectional Fiber Reinforcement

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Stretchable Unidirectional Fiber Reinforcement

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Table of Contents

Stretchable Unidirectional Prepreg

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Abstract

Small staggered cuts were made in unidirectional prepreg to allow it to stretch. The cuts were made either just locally where required for a complex mold, or throughout the whole prepreg. Three tests were performed: uni-axial tensile tests of flat specimens, mold conformability tests to evaluate manufacturability, and manufacturing and structural tests of round tubes. The cuts reduced the tensile strength by less than 20%. The conformability tests used a complex shaped mold for part of a radome and the locally cut prepreg significantly simplified layup and reduced fiber waviness and hammocking. The tubes were made by winding prepreg on male mandrels, and then transferring the prepreg to a female mold for curing. The tubes made with stretchable prepreg were considerably less affected by mandrel size, had excellent surface finish, and within 3-6% possessed the same strength as the best tubes made with conventional prepreg.

Keywords: Stretchable, Prepreg (E), Lay-up (manual/automated) (E), Mechanical testing (D)

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Introduction

There are different configurations available for fiber reinforcements, including woven, unidirectional, and random. Unidirectional reinforcements are typically the strongest, with long unbroken fibers and no waviness as in woven reinforcements. While unidirectionals are the strongest, they have rather poor ability to conform to complex mold surfaces during the manufacturing process. This often leads to either "hammocking" if the layup is taught, or fiber waviness if the layup is loose. Hammocking is when the prepreg cures without contact to the mold or adjacent plies. Many high performance structures could benefit from the use of unidirectionals prepreg but their lack of conformability prohibits their use.

A number of industry suppliers have proposed fiber reinforcements made with tows of discontinuous but still aligned fibers; see e.g. Black [1]. Theses stretchable reinforcements seem to have appeared in the 1980's, but not gained too much popularity until recently due to increased demand on high speed automated manufacturing. The material presently studied, unidirectional prepregs with a number of small cuts, could be either stretchable throughout, or just locally as mold shape may require. With only local cuts, i.e., local stretchability, parts can be made with the strength of unidirectionals and the manufacturing ease of woven or random reinforcements.

Prepreg with Cuts

Unidirectional reinforcements derive their high strength and stiffness from having straight, continuous fibers. However, unidirectional prepregs typically have very poor drapability and are difficult to lay into compound curvature molds without creating hammocks or fiber waviness. Both of these defects adversely affect mechanical properties. In particular they can severely reduce compression strength.

The proposed solution is a unidirectional prepreg with a large number of small staggered cuts in such a pattern as to allow the prepreg to stretch and conform to a mold when placed under vacuum. The pattern of the cuts was designed to retain high tensile strength and stiffness of the finished composite. Some cut patterns for the stretchable unidirectional material is shown in Fig. 1. The cut pattern should be designed to maximize load transfer (shear lag) between fibers. The length between repeating cuts of the same fiber would be expected to be

on the order of 25-100mm for small complex parts, while much longer for large parts and parts made in less complex shaped molds. The cuts could also be employed locally, as necessary, in a part that has regions of both simple and complex features. By tailoring the cuts in the prepreg to the complexity of the mold, the prepreg can be made to stretch where needed while retaining the high strength and stiffness of a regular (non-cut) prepreg elsewhere. Fig. 5 shows a part of a radome that was made with a prepreg that was cut locally, only near the corners. Preliminary tests suggest that the optimal length between cuts is proportional to the local radius of curvature of the mold.

Two different processes were evaluated for making the cuts in the prepreg. First, a laser cutting system was utilized. While good geometric definition was possible (thin accurate cuts), an unacceptable amount of resin was cured by the laser resulting in poor properties of the cured composite part. Subsequently, a computer numerically controlled (CNC) pneumatic razor blade system, Fig. 2, was developed to punch through the prepreg in a definable pattern. This process, while much slower, had the distinct advantage of not heating the prepreg and therefore yielded better material properties.

Design of the Cut Pattern

The cut prepreg can be likened with interlocked "forks" as sketched in Fig. 3. The load transfer between the "forks" is presumably mainly by shear in the matrix along the dashed vertical lines in Fig. 3, as well as to adjacent plies. In order to create a stretchable prepreg material that after cure retains much of the strength of a conventional prepreg composite, careful consideration should be given to the location of the cuts. The length of the individual cuts should be small to retain strength, in particular in smaller parts. For example in a strip of 10 mm width made from a single layer of unidirectional prepreg, if the width of a cut were 2 mm then one would not expect to retain more than 80% of the strength of a strip made without cuts. Using the CNC pneumatic razor cutter, clean, sharp cuts of 1 mm length could be made consistently. Smaller cuts were not as consistent. The cuts must to be located such that the unidirectional prepreg can stretch. Due to slight fiber waviness in a prepreg, the cuts needed to be a little longer than what would be theoretically necessary for a "perfect" prepreg

(with perfectly straight and parallel fibers). Tests revealed that using a pattern that would be stretchable with 1 mm cuts in a perfect prepreg, would be stretchable if a razor blade of 1.1 mm length were used. Apart from the tensile test screening presented in the next section, a 1.1 mm wide razor blade was used for all subsequent research.

Tensile Tests

Plain flat tensile test specimens with five different cut patterns were made and tested to failure. The five patterns are shown in Fig. 1, and their pertinent dimensions are given in Table 1. The shear lag length and the fraction of uncut fibers in the worst cross section varied between the cut patterns.

To make the specimens, Gurit SE84LV/HEC/200/400/37% unidirectional carbon fiber prepreg was used. This prepreg has a surface density of carbon fiber of 200g/m^2 and a resin content of 37% by weight, yielding a total weight of 317.5 g/m^2. The specimen layup was $(90°_2, 0°_2, 90°)_s$ where 0° is the test direction, resulting in a thickness of 2 mm. Only the 0° plies were cut. The prepreg was laid up on a 9.5mm thick release coated aluminum mold, covered by peel ply, perforated release film, breather, and sealed with a vacuum bag. After every two layers the prepreg was debulked under vacuum for one hour. Multiple specimens, with different cut patterns and a few specimens of each pattern, were made simultaneously in large plates. The plates were cured under vacuum in an oven. The cure schedule was to ramp the temperature at 1 °C/min and cure the part for 3.5 hours at 100°C. After cure the plates were demolded and cut into straight sided specimens 25 mm wide by 350mm long using an abrasive waterjet cutter. The tensile tests were performed in an MTI modified Instron test frame. The load rate was 0.5 mm/min. Ten specimens of each configuration were tested, Table 1. The fracture surface always followed along the cut pattern, propagating quickly across the entire specimen. One example is shown in Fig. 4. The tensile tests in general showed, as expected, that specimens with small dispersed cuts arranged to give long shear lag lengths retained high tensile strength better than specimens with large or closely spaced cuts. Cut pattern 1 (see Fig. 1) led to the highest tensile strength, retaining 82% of the strength of the control specimen which was made with conventional unidirectional prepreg without any cuts (Table 1).

Mold Conformability Tests

A mold conformability test was performed using both regular prepreg and the new stretchable prepregs. The mold, shown in Fig. 5, was made to have many of the geometric features of a certain forward-looking supersonic radome. The mold was CNC milled from a 75mm thick piece of aluminum. The goal of the conformability test was to determine whether the stretchable prepreg would allow for highly complex parts to be made with unidirectional carbon fiber prepreg. The test consisted of laying up parts with both types of prepreg, debulking them under full vacuum for 24 hours at 22°C and then another 10 hours at 35°C, then ramping the temperature at 1°C/min and cure the part for 3.5 hours at 100°C. This cycle was chosen to allow the resin to reach a low viscosity, making it relatively easy for the carbon fibers to slide relative to each other and thus conform better to the mold. More research may be necessary to optimize the cure cycle. After cure the parts were inspected for hammocking and fiber waviness as well as general quality and surface finish.

As seen in Fig. 5 the mold consisted of a bull nose on a rectangular cross section with rounded edges. It is difficult to achieve a good part because the radii at both the bull nose and along the edges are quite small. Parts made with regular prepreg had mild to severe hammocking and fiber waviness attributed to the lack of stretch; see Fig. 6. It is important for a radome to have a good geometry and constant thickness for proper transmission of electro-magnetic waves; any hammocking essentially renders the part useless. It may be noted that a radome would in general not be made of carbon fiber, but quartz or glass.

The parts for the conformability tests had the layup (90°,0°,90°), where the 0° direction was along the length of the part. As mentioned, parts made with regular prepreg suffered from severe hammocking, fiber waviness, and very poor finish near the corners. However, parts made with stretchable prepregs were essentially perfect; see Figs. 6-7. The stretchable prepreg was cut only near the corners, thus most of the part retained the full strength and stiffness of a regular unidirectional prepreg. The stretchable prepreg was easier to lay up, and during the debulking at slightly elevated temperature the prepreg moved down and conformed perfectly to the mold.

It can be seen in the finished parts (Fig. 7) that the gaps by the cuts opened up slightly (on the order 0.5 mm). However, excess epoxy in the prepreg fully filled these "gaps" and the resulting surface finish was excellent. Multiple parts were made with different distance between the cuts in order to determine its effect on how well the prepreg could be made to conform to the varying radii of curvature in the part. Experimentally, distance between cuts up to approximately twice the radius of curvature was found to allow for adequate stretching of the prepreg. All tests used the cut pattern 4 (see Fig. 1).

Round Tubes, Manufacturing and Structural Tests

Structural tests were performed on tubes curing in a female mold using both regular and stretchable prepregs. The layup was ((+80°,-80°), $0°_4$, $(+80°,-80°)_2$), yielding a wall thickness of 2mm. Only the hoop fibers (+/-80°) were cut. Tubes with hoop fibers are notoriously difficult to make in female molds with regular prepreg. The tubes using regular prepreg were wound on male mandrels whose size had to be very carefully determined. If the prepreg were wound on a too small mandrel then the hoop fibers would restrain the composite from conforming to the female mold and the geometry as well as the surface finish of the cured tube would be very poor (as shown in Fig. 8). If the prepreg were wound on a slightly too large male mandrel, then the hoop fibers would create fiber waviness and/or a bulge when the stack was placed in the female mold (Fig. 9). Only a very well controlled mandrel will lead to a good tube. A number of iterations were required to reach this size.

The stretchable prepreg, on the other hand, allowed very good tubes to be made very easily. A significantly undersized male mandrel was used. The wound stack was placed in the female mold and allowed to stretch under vacuum and slightly elevated temperature until the fibers perfectly conformed to the female mold. Again the cuts would open up slightly and be filled with epoxy from the prepreg. An example tube is shown in Fig. 10. Two good tubes, one made with regular and another with stretchable prepreg, were tested to failure under three-point bending, Fig. 11. Both tubes were 600mm long and 39mm in outer diameter. The tube made with stretchable prepreg failed at a load of 675N while the tube made with regular prepreg failed at a load of 693N (the 2.7% difference is not significant).

Each tube was then cut into ten 25.4mm long sections and crushed under transverse load as shown in Fig. 12. The specimens made with regular prepreg were found to be stronger than those with cuts by 6 percent. The reduction should be expected since the hoop fibers would carry this load and these fibers were cut.

Summary and Conclusions

For the initial tensile tests five different cut patterns were used to make the prepreg stretchable and these resulted in specimens with different strengths. In general there was a clear increase in tensile strength when the total shear length increased (Table 1). However, specimens made with Pattern 4 had the longest shear length but were considerably weaker than specimens made with Pattern 1. The reason appears to be that the failure of Pattern 4 was a mixture of shear between fibers, and fiber fracture. A more pure shear failure would lead to quite long and narrow splinters; however, these splinters appear to have broken off resulting in a lower overall strength of Pattern 4. Pattern 2 had a short shear length, and in its worst cross section 50% of the fibers were cut. Specimens made with this pattern had only 27% of the strength of the control specimens.

For the mold conformability tests using the quite intricate radome mold, a prepreg with cuts only by the corners in the mold was used. Layup was simplified when compared to conventional prepreg, and the resulting radome part was superior. The tests indicated that the distance between cuts should be approximately twice the radius of curvature to make parts of good quality.

The tubes, made by winding prereg over a male mandrel and then transferred to cure in a female mold, turned out very well when the stretchable prepreg was used. Conventional prepreg can also be used but require tight tolerances on the mandrel and repeated debulking in order to avoid hammocking (when using too small mandrel) or fiber waviness and internal bulges (when using a too large mandrel).

While this initial investigation of a stretchable unidirectional prepreg appears very promising there is still much work to be done. More in-depth testing should be performed in at least three main areas. First, different cure cycles should be evaluated to maximize stretch while minimizing the number of cuts necessary, thus resulting in stronger parts. Second, a mathematical model for cut locations and frequency should be developed so cuts can

be placed only where needed in a part. And third, extensive testing should be performed to evaluate fatigue performance, ductility, impact strength, compression after impact, damage tolerance, etc., of parts made from stretchable prepreg.

Acknowledgements

This work was supported by ARO Grant W911NF-08-1-0386, with Dr. David M. Stepp as program manager.

References

1. Black, S., "Aligned Discontinuous Fibers Come of Age," High Performance Composites, March, 2008.

Tables

Table 1. Geometry definition and tensile strength of 25 mm wide specimens made with the five different cut patterns.

	Width of cuts	Max. No. Cuts at Worst Cross Section	Fraction Uncut Fibers at Worst Cross Section	Shear Length	Tensile Strength (Avg.)	Strength Relative to Control
Pattern 1	1 mm	5	0.8	480 mm	38277 N	0.82
Pattern 2	6.25 mm	2	0.5	150 mm	12649 N	0.27
Pattern 3	2.08 mm	1	0.92	384 mm	25837 N	0.55
Pattern 4	1.56 mm	1	0.94	506 mm	27775 N	0.59
Pattern 5	1.37 mm	2	0.89	180 mm	18650 N	0.40
Control	-	-	1	N/A	46858 N	1

Figures

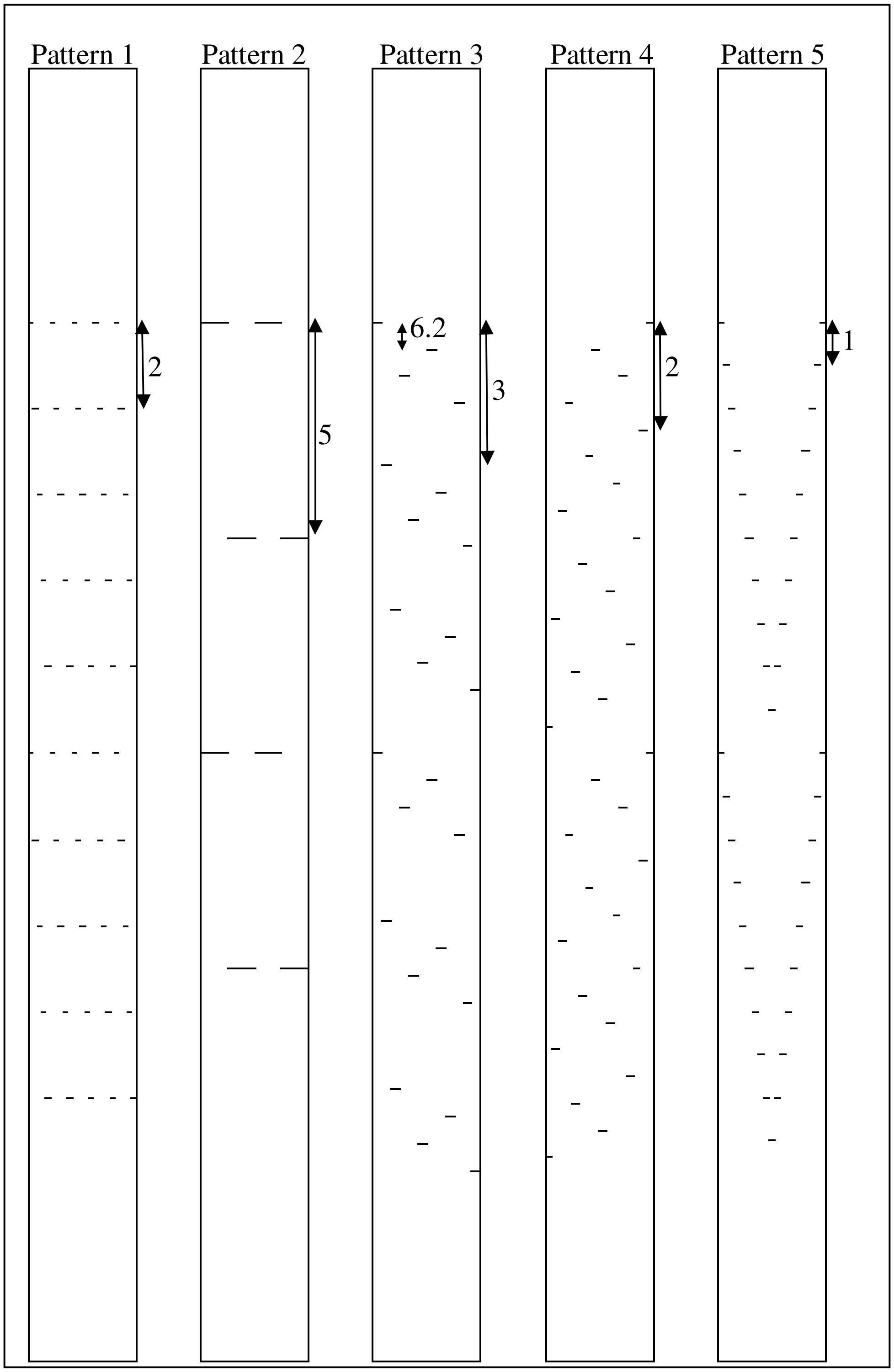

Fig. 1. Cut patterns 1-5 from left to right shown as they would appear on a 25mm wide prepreg strip. All dimensions in millimeters. The cut patterns are repeated in the axial direction after 100 mm.

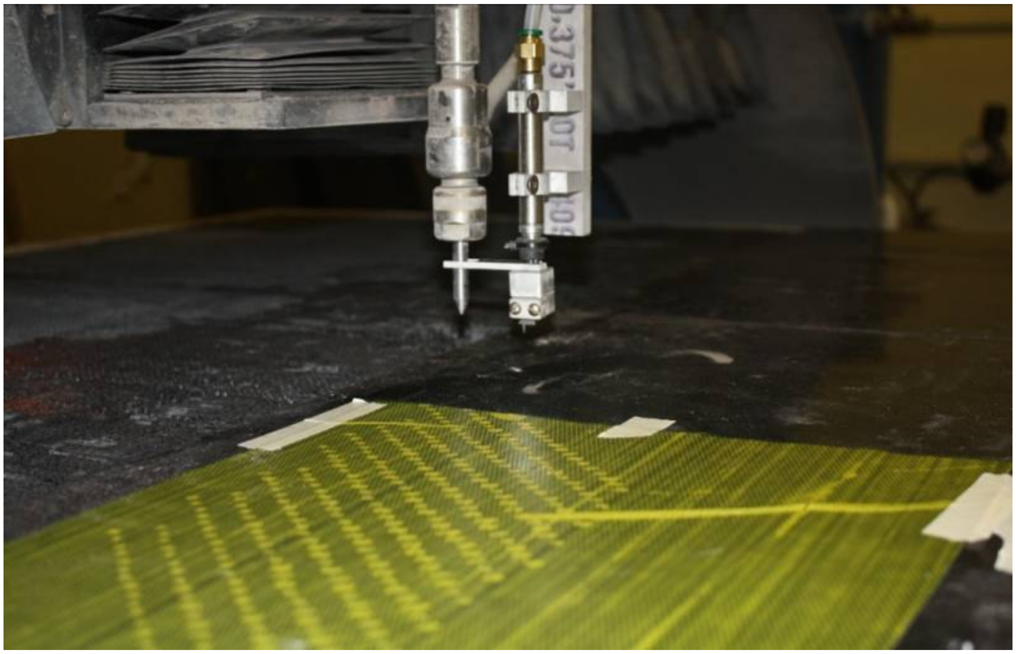

Fig.2. Cutting the prepreg using a pneumatic CNC cutter, made for this project by mounting a razor blade and pneumatic cylinder to a CNC waterjet cutter.

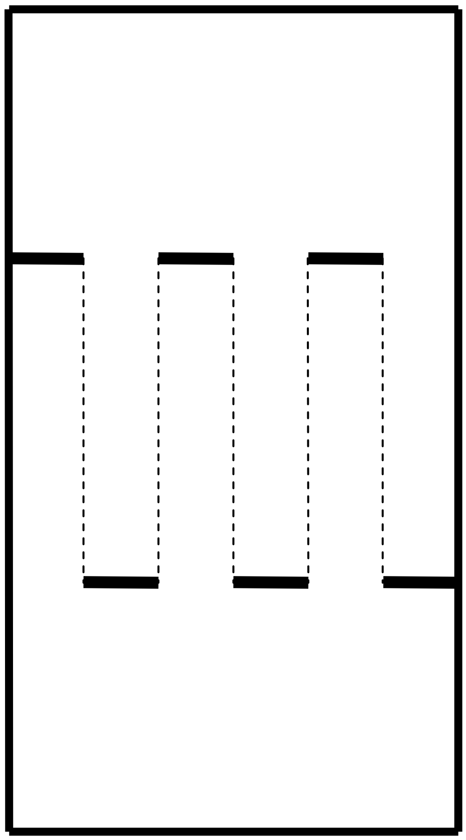

Fig. 3. Sketch indicating shear lag length (total length of dashed lines) in the cut prepreg. Short horizontal lines indicate cuts. In this pattern 50% of the fibers are cut at the worst cross sections.

Fig. 4. Tensile specimen after failure (Pattern 5), clearly showing how the fracture followed the cuts.

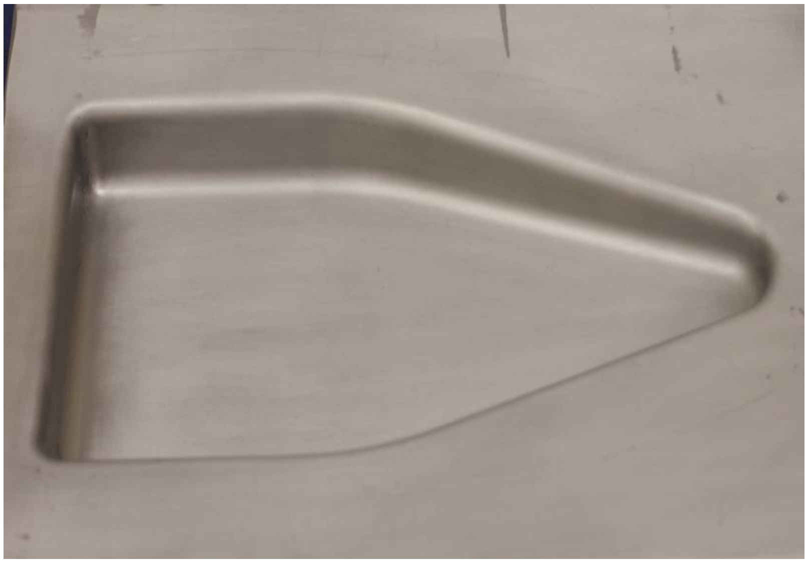

Fig. 5. Supersonic Radome Mold

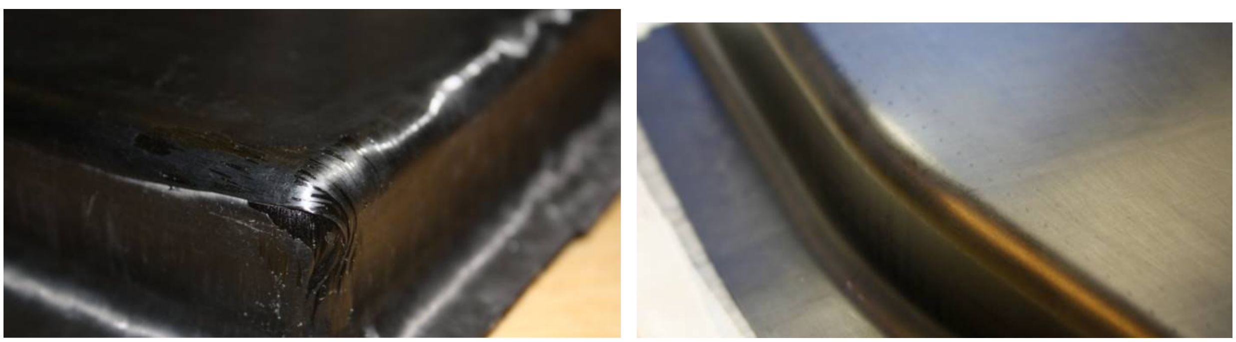

Fig. 6. Left: radome part made with conventional prepreg which resulted in both hammocks and fiber waviness. Right: the same part made with locally stretchable prepreg.

Fig. 7. Nose of Radome. Notice the gaps created by stretching. The stretching cuts were made only locally in the corners.

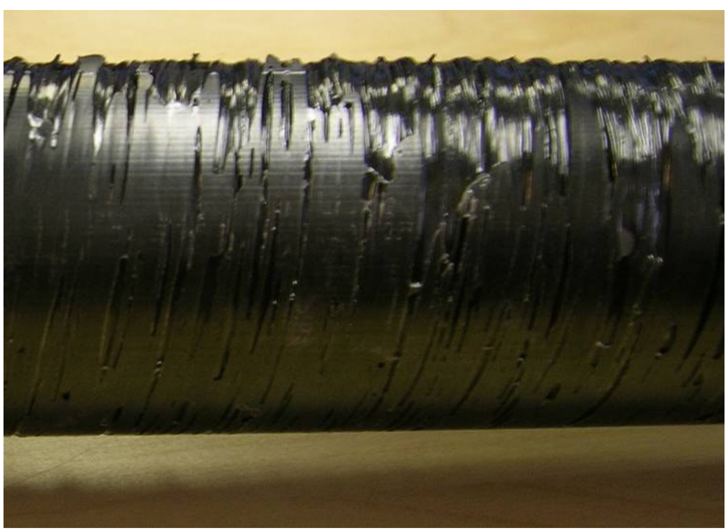

Fig. 8. Tube wound with conventional prepreg on an undersized mandrel, and then cured in a female mold. Note severe hammocking.

Fig. 9. Tubes wound with conventional prepreg on slightly oversized mandrels, showing fiber waviness (left) and an internal bulge (right)

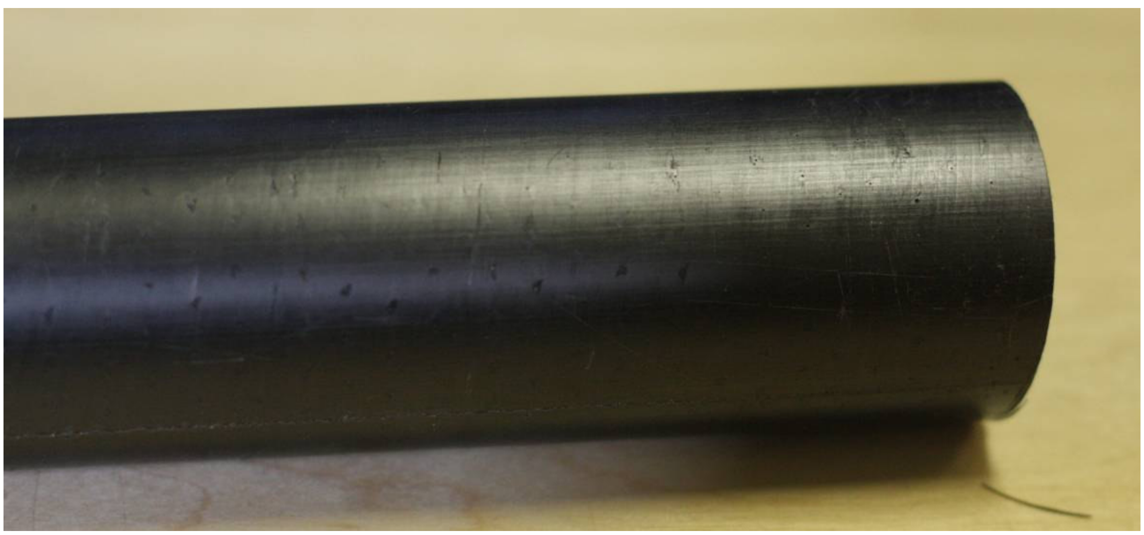

Fig. 10. Tube made with stretchable prepreg, fully conformed to female mold. Note the small areas where stretching occurred. Gaps created were fully filled with resin during the curing process.

Fig. 11. Three point bend test of carbon fiber tube.

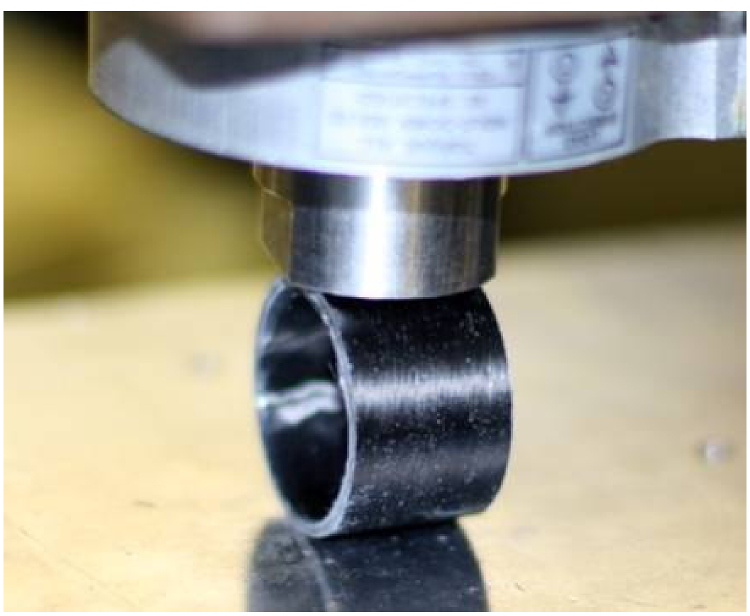

Fig. 12. Transverse crush test of tube specimens.